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Impacts of large-scale penetration of wind power on day-ahead electricity markets and forward contracts

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ABSTRACT

Utilization of renewable energy resources, especially wind power, for producing electric energy is growing fast in the world. Besides the environmental advantages, the variability, unpredictability, and uncontrollability of the wind turbines' output power face the market players with different financial risks. Producers and consumers prefer to have a stable income in the power system and try to avoid the uncertainties and fluctuations in their profits. In this situation, forward contracts are used as efficient tools for helping the market players to hedge themselves against these risks. Since market players participate in both forward and day-ahead markets, their actions in each market affect the other market. So, day-ahead and forward markets affect each other. In this paper, the behavior of market players in the forward and day-ahead electricity markets in the presence of large-scale wind farms are studied. To this end, first, the contracting period is modeled considering different outcomes for the delivery period and then, the delivery period is modeled considering the contracting period outcomes. Equilibrium models are presented for each model. Both uniform and pay-as-bid pricing models for the day-ahead market are considered in the modeling procedure. A recently introduced risk management method called concern scenarios is upgraded and applied to model the risk management preferences of market players. Simulation results are presented, analyzed, and compared for models by applying them to a test system case study.

1. Introduction

The utilization of wind power as the main renewable energy resource for producing electric energy is growing fast in the world. In some countries like Denmark, Germany, and Spain a considerable share of electricity demand is supplied by wind power [1]. Large-scale integration of wind power in the power system confronts the market players and system operators with some operational challenges. From the viewpoint of the financial issues, unpredictable and uncontrollable variations in the output power of the wind power plants result in variation in the electricity market clearing price (MCP) and scheduled power of producers and consumers. This leads to variation and uncertainty in the profit of both producers and consumers and increases the risk of losing money in the electricity market. Financial derivatives can be used as a useful tool for market players to hedge themselves against the risks of undesirable profit fluctuation [2]. Forward contracts are one of the relevant financial tools and nowadays, a considerable quantity of power in the power system is traded through the forward contracts. A forward contract is a bilateral agreement contract between a producer and a consumer that implies the producer to sell a given power quantity to the consumer throughout a pre-specified time period at a fixed price in \$/MWh [3]. Forward contracts can be agreed in a market that is called the forward market [4]. Market players are allowed to trade energy via both forward and day-ahead electricity markets. Changing the behavior of market players in each market affects their strategy in the other market. Hence, it can be said that there are mutual impacts between the forward and day-ahead markets. Studying the behavior of market players in the power system should be performed considering both forward and day-ahead electricity markets and their mutual impacts on each other.

Forward and day-ahead electricity markets studies have already appeared in a wide range of research works. In [5] two separate mathematical models for a consumer and a producer for optimal power allocation between the day-ahead electricity market and forward contracts are introduced. In [6] a mathematical model for supplying a large-scale electricity consumer through self-production, buying from

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Nomenclature

A. Indices

i or u	Power system producers
j or l	Power system consumers
S	Concern scenarios

B. Sets

P	Set of producers
C	Set of consumers
S	Set of concern scenarios

C. Constants

a_i	Intercept of marginal cost function of producer *i*
b_i	Slope of marginal cost function of producer *i*
c_j	Intercept of marginal utility function of consumer *j*
d_j	Slope of marginal utility function of consumer *j*
$\bar{Q}_i/\underline{Q}_i$	Maximum/minimum output power of the producer *i*
$\rho^p_{i,s}/\rho^c_{j,s}$	Concern value of scenario *s* form the viewpoint of producer *i*/ consumer *j*

D. Variables

α^f_{ij}	Intercept of bid function of producer *i* to consumer *j* in forward contract market
ϵ^f_{ji}	Intercept of offer function of consumer *j* to producer *i* in forward contract market
$\alpha^d_{i,s}$	Intercept of bid function of producer *i* at concern scenario *s* in day-ahead market
$Q^{fp}_{ij}/\ Q^{fc}_{ji}$	Contracted power of producer *i* with consumer *j*/consumer *j* with producer *i*
$Q^{dp}_{i,s}/Q^{dc}_{j,s}$	Scheduled power of producer *i*/ consumer *j* in day-ahead electricity market at concern scenario *s*
F^{fp}_{ij}/F^{fc}_{ji}	Price of forward contract between producer *i* and consumer *j*/consumer *j* and producer *i*
λ^d_s	The Lagrangian multiplier of power equality constraint in the system and the market-clearing price of day-ahead electricity market at concern scenario *s*
$\bar{\mu}^{dp}_{i,s}/\underline{\mu}^{dp}_{i,s}$	Lagrangian multiplier associated with maximum/minimum generation capacity of producer *i* at concern scenario *s*
$\bar{\mu}^{dc}_{j,s}/\underline{\mu}^{dc}_{j,s}$	Lagrangian multiplier associated with maximum/minimum consumption of consumer *j* at concern scenario *s*
$\mu^{dp+}_{i,s}/\mu^{dc+}_{j,s}$	Lagrangian multiplier associated with positivity of output power of producer *i*/ consumer *j* in day-ahead market at concern scenario *s*
$\mu^{fp}_{ij}/\mu^{fc}_{ji}$	Lagrangian multiplier associated with minimum quantity of power for forward contract between producer *i* and consumer *j*/consumer *j* and producer *i*

the day-ahead market, and weekly and monthly forward contracts is proposed. In [5] and [6] dynamic programming is applied to solve their problems. The profit optimization problem of a wind hydro-pump storage power plant that is allowed to trade its output power through the day-ahead electricity market and forward contracts is solved in [7]. In [8] a stochastic model for optimal decision-making of a distribution company for participation in the forward contracts and day-ahead market is formulated. In [9] optimal bidding strategy for a price-taker producer in the day-ahead electricity market and weekly forward contracts is studied. A multi-stage mixed-integer stochastic model for determining the optimal trading strategy of a risk-averse producer in the day-ahead electricity market, forward contracts and option contracts is introduced in [10]. In [11] a model for the optimal operation of a day-ahead electricity market parallel with the reserve market and forward contracts is introduced. It is assumed that the prices of the contracts are predetermined. Market players' bid their marginal costs in the day-ahead market, and the required reserve is assumed to be certain, known and constant. In [12] a Nash equilibrium model for a power system with only forward contract market is proposed. According to this method, each producer submits his/her marginal cost to each consumer for obtaining the volume of forward contracts. The day-ahead electricity market has not been taken into account in [12]. In [13] a Cournot Nash equilibrium model is proposed for joint day-ahead and forward market. Cournot game is used for both day-ahead and forward markets, strategic gaming of consumers in forward contracts are not considered, risk management is not modeled and all demand is aggregated in a single load. In [14] an iterative algorithm to model the negotiation process of a bilateral contract between a producer and a consumer parallel with the day-ahead electricity market is proposed. In [15] supply function equilibrium of a day-ahead electricity market parallel with forward contracts is investigated. Impacts of electricity market prices on the volume of forward contracts, the generation capacity of producers, and gaming of the consumers in the contract negotiation process are ignored in the proposed method in [15]. In [16] the optimal price adjustment problem of forward contracts in a power system with fuel-bases generators in a transmission network, suppliers as intermediaries and consumers with flexible and inflexible loads and renewable resources in a distribution network is solved using an iterative algorithm. The volumes of forward contracts are assumed to be known and constant. In [3] optimal gaming of the producers and consumers in forward market and day-ahead electricity market is studied. Impacts of forward contracts on the price of the day-ahead electricity market are ignored in this work. In [17] a mathematical model for supply function Nash equilibrium of an electricity market parallel with a forward market is proposed. Uniform pricing is considered for the day-ahead electricity market.

In this paper, Supply Function Equilibrium (SFE) of a power system with a day-ahead electricity market parallel with a forward contract market is modeled. This paper is an improvement of the proposed method in [17]. The main contributions and improvements of this paper are as follows:

1. In this paper, first, the contracting period is modeled considering its impacts on the day-ahead market and then the delivery period is modeled considering the impacts of contracted powers on the day-ahead market, while in [17] only one aggregated model is proposed. In fact, the proposed model in this paper is more realistic than the proposed model in [17].
2. Both uniform and pay-as-bid pricing mechanisms for the day-ahead market are considered in this paper, while [17] considers only the uniform pricing method for the day-ahead market.
3. In this paper, uncertainties related to the output power of large-scale wind farms (WFs) at the delivery period are considered in the market players' optimization problems in the contracting period. This uncertainty is not considered in the proposed method in [17].
4. In order to model the risk management behavior of the market players, the proposed risk management method in [17] is upgraded to present a more realistic vision of the market players' risk management preferences.
5. Upper and lower bounds of consuming energy by consumers are also considered in the proposed model in this paper.

The rest of the paper is organized as follows: the problem is defined and assumptions are presented in section II. In section III, the forward contract market and day-ahead electricity market are formulated. In section IV, the process of obtaining SFE in the contracting period is explained for both uniform and pay-as-bid models. In section V, SFE of the delivery period for both uniform and pay-as-bid models is presented. Simulation results are analyzed and discussed in section VI, and finally, conclusions are presented in section VII.

2. Problem definition and assumptions

A power system including some fuel-based strategic power producers, large-scale consumers, and price taker WFs is considered. It is assumed that all the producers and consumers are connected to the grid. Each producer can own one or some units and is introduced with a single aggregated marginal cost function. Each consumer can also represent retailers or large-scale loads and are modeled with an aggregated marginal utility functions. The marginal cost function of producer i i.e., MC_i and marginal utility function of consumer j i.e., MC_j in uncertainty scenario s are as below:

$$MC_{i,s} = a_i + b_i Q_{i,s}^{dp} \tag{1}$$

$$MC_{j,s} = c_j - d_j Q_{j,s}^{dc} \tag{2}$$

The total installed capacity of the wind power is modeled as a single WF with uncertain output power. In this condition, there is considerable uncertainty related to the power supply and consequently the day-ahead market prices and profit of the market players in the future. This uncertainty confronts the market players with the risk of losing money in the day-ahead electricity market. Hence, market players involve in long-term forward contracts parallel with the day-ahead market to hedge themselves against this risk. Since for trading energy at a specific hour of the delivery period, market players participate in both forward and day-ahead markets, there could be mutual impacts between these markets. The correlation between forward and day-ahead markets is illustrated in Fig. 1. Forward contract prices are influenced by the estimation of day-ahead market prices and day-ahead market prices are affected by the quantities of power that are transferred from the day-ahead market to forward contracts. So, changing a parameter at forward or day-ahead market affect the behavior of market players in both markets.

In this paper, the behavior of the risk-averse producers and consumers in the joint forward and day-ahead electricity markets is studied. The problem is solved from the viewpoint of the Independent System Operator (ISO). Risk management preferences of the market players are considered to be different. The proposed concern scenario method in [17] is upgraded in this paper to model the risk management behavior of the market players. According to the definition of forward contracts, there are two important time periods in the problem, contracting period and delivery period. In the contracting period, the contract negotiations are performed and the price and quantity of contracts are agreed. In the delivery period, which can be up to one year after the contracting period, first, the contracts are exercised and settled by physical delivery, and then, producers and consumer participate in the day-ahead market to sell the rest of their free generation capacity or buy their remained required demand. So, there are two games in two different time periods that affect each other. A game at the contracting period in the forward market to gain the optimal contracts based on the risk management preferences of the market players, considering different possible scenarios for the day-ahead market, and a game at the delivery period in the day-ahead market considering the agreed prices and quantities of contracts. In this paper, the behavior of market players in both of these games are modeled. To this end, it is assumed that the system is in its Nash equilibrium at both games and the market players' behavior is studied in the equilibrium conditions. Hence, a Nash equilibrium model for the game at the contracting period and a Nash equilibrium model for the game at the delivery period are presented. It should be noted that while the equilibrium models are presented separately, their mutual impacts on each other are considered in each model. In fact, in both contracting and delivery periods, market players maximize their profit in the aggregation of both forward and day-ahead markets. In the contracting period, they consider different scenarios for the day-ahead market in the delivery period, and in the delivery period, they consider their contracted powers in the contracting period.

The supply function model is considered for both forward and day-ahead markets which turns the problems into SFE models. Based on the definition of the forward contracts, the uniform pricing model is considered to model the forward contract between each producer and consumer. Either uniform or pay-as-bid pricing mechanisms can be chosen for the day-ahead electricity market. In order to present a comprehensive and comparative study, both the contracting period and delivery period equilibrium models are presented considering both uniform and pay-as-bid pricing mechanisms for the day-ahead market. So, in fact, in this paper, four equilibrium models are presented:

1. A SFE model for contracting period considering uniform pricing in the forward and day-ahead markets (UFUD).
2. A SFE model for delivery period with uniform pricing in the day-ahead market (UD) considering the agreed contracts in the contracting period.
3. A SFE model for contracting period considering uniform pricing in

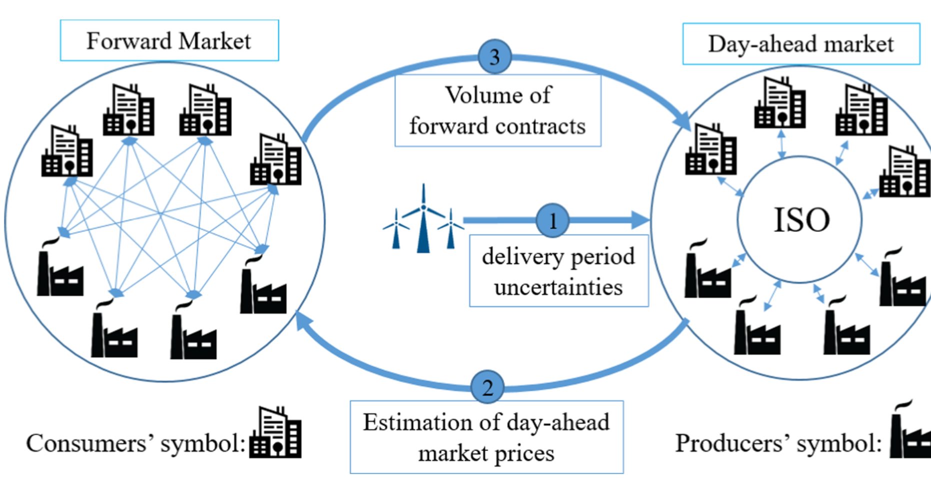

Fig. 1. Mutual impacts of forward contracts and day-ahead market.

the forward market and pay-as-bid pricing in the day-ahead market (UFPD).
4. A SFE model for delivery period with pay-as-bid pricing in the day-ahead market (PD) considering the agreed contracts in the contracting period.
1. Transmission system constraints are not considered in the models to avoid complexity. It is assumed that the delivery period is one hour of a specific day in the future. However, it can be easily extended to several consecutive hours.

2.1. Market players' actions, and forward and electricity market settlement procedure

All producers and consumers behave strategically in the forward market. It is assumed that each producer can have a contract with each consumer and vice versa. Intercepts of the marginal cost and marginal utility functions of producers and consumers are chosen as their decision making variables in the forward market. In the day-ahead market, producers behave strategically, but the consumers are price takers to supply all their demand anyhow. In fact, consumers are mostly large-scale industrial loads and companies that have to provide the required electricity demand of their loads. Strategic bidding in the day-ahead market confronts these consumers with the risk of not winning their required power for their demands in the day-ahead market. This imposes significant costs to these market participants. So, they bid their marginal utility function to the ISO to assure winning all their required power and receive the day-ahead market price as the electricity price. It should be noted that consumers are modeled as elastic loads and they are sensitive to the market prices. So, they react to the day-ahead market prices. They just do not game in the day-ahead electricity market to avoid the risk of not dispatching or partially dispatching in the day-ahead electricity market. Programs like demand response or self-power generation for each consumer can affect the elasticity of consumers' loads and can be implemented in their marginal utility function. The intercepts of the marginal cost functions of the producers are used as their decision making variables in the day-ahead electricity market. Since WFs are mostly in long-term contracts with governments in fixed prices, it is not necessary for them to participate in the forward and day-ahead markets strategically and all their output powers are always purchased by the ISO.

As mentioned before, it is assumed that the forward contracts are settled physically, which means that all the agreed contract quantities should be traded between the market players at the agreed prices during the delivery period. Then, the day-ahead electricity market runs for the rest of the consumers' demand and free capacity of producers one day before the delivery period. The settlement of the day-ahead electricity market depends on the pricing mechanism of the market. If uniform pricing is considered for the day-ahead market, a uniform price will be received from the consumers and paid to the producers. If pay-as-bid pricing is considered for the day-ahead market, each market player's generation or consumption will be settled based on his/her bid to the ISO.

2.2. Wind power generation uncertainty modeling

The time interval between the contracting period and the delivery period could be weeks, months or years. So, there is considerable uncertainty related to the output power of WFs in the delivery period. Some discrete scenarios are defined based on the installed wind power capacity, wind speed characteristics of WFs and correlation between the output powers of WFs. These scenarios are defined as $Q_s^w \ \forall \ s \in S$ and it is assumed that scenarios are sorted such that $Q_s^w \le Q_{s+1}^w$. This property is used later to present the proposed risk management method in a clearer way.

2.3. Proposing the upgraded risk management method

The concern scenario method was introduced in [17] to model the risk management preferences of market players. In this paper, this method is upgraded to present a more realistic vision of the market players' concerns. According to the concern scenario method, market players pay more attention to the scenarios that reduce their profit in the system. A producer (consumer) that is more concern about decreasing (increasing) the market prices in the delivery period and hence, pays more attention to these scenarios. In the concern scenario method, this attention is modeled by considering more probability for these scenarios. In this paper, Exponential Distribution is used to model the variation of the concerns of market players by changing the uncertainty scenarios i.e., the output power of the WFs. The probability density function (PDF) of the exponential distribution is as below:

$$e(x) = \beta e^{-\beta x} x \ge 0 \tag{3}$$

Increasing the output power of the WFs, increases the competition in the system and leads to reducing the market prices that results in reducing the producers' profit and increasing the consumer's profit. So, producers (consumers) are worried about increasing (decreasing) the output power of WFs in the delivery period and according to the concern scenario method, more probability should be assigned for the scenarios that show increase (decrease) in the output power of the WFs. Since it is assumed that $Q_s^w \le Q_{s+1}^w$, then for producers, we should have $\rho_{i,s}^p \le \rho_{i,s+1}^p$ and for consumers, we should have $\rho_{j,s+1}^c \le \rho_{j,s}^c$. Beta PDF that is used in [17] cannot guaranty this property for all scenarios in all cases because Beta PDF is not a monotonic function for all values of its parameters. But Exponential PDF that has a monotonic function can represent this feature correctly. Fig. 2 illustrates this fact. As shown in Fig. 2, while the concern values extracted from exponential PDF follow the trend of concerns of a consumer for all scenarios, this trend can be inverse for some scenarios of Beta PDF, i.e. by increasing the market price the concern value of the consumer may reduce in Beta PDF. Hence, choosing the exponential PDF is more reasonable than the Beta PDF. It is noticeable that Beta function can also be plotted as a monotonic function if its parameters are adjusted correctly, but, in this case, there is also the risk of obtaining infinite concern values for some scenarios. Using one variable to control the concerns of market players is another advantage of using exponential PDF instead of Beta PDF in which two parameters should be adjusted for obtaining the concern

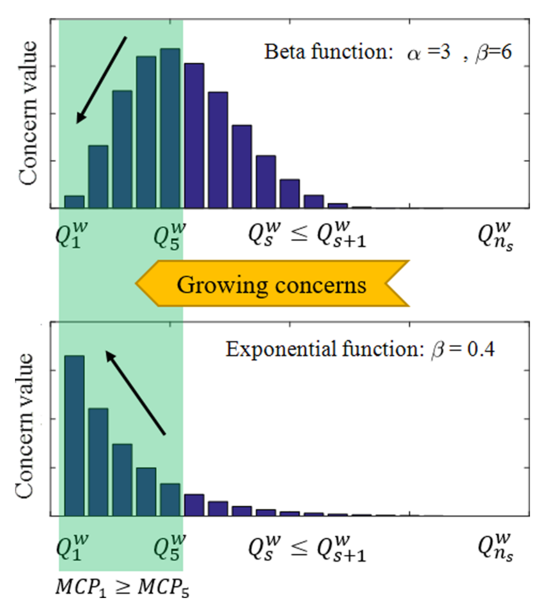

Fig. 2. Illustrating the advantage of Exponential PDF compared to Beta PDF for extracting concern scenarios.

values. Simulation results also show more volume of concluded forward contracts when the exponential PDF is used instead of the Beta PDF.

Exponential PDF can be easily assigned to model the risk management preferences of consumers because for $Q_s^w \le Q_{s+1}^w$ we have $e(Q_{s+1}^w) \le e(Q_s^w)$. In order to, adapt Exponential PDF for producers, it is assumed that for n_s scenarios, n_s values are generated by Exponential PDF. Then, the first wind power uncertainty scenario is assigned to the last generated probability of Exponential PDF, the second scenario is assigned to the one before the last generated probability and so on. These assignments are illustrated in Fig. 3 for an arbitrary producer i and consumer j. parameter β represents the intercept of Exponential PDF with the Probability-axis. Each the value of β increases, the probability of scenarios that market players are more worried about them increases. So, parameter β can be used to show the amount of concern of market players about the future. A producer i (consumer j) with a greater value for β_i^p (β_j^c) represents a more concern market player. According to Fig. 3, producer i is less concerned than consumer j about the output power of WFs in the delivery period.

3. Forward market and day-ahead electricity market modeling

Forward and day-ahead electricity markets modeling for all models are the same. The difference of the cases is in the settlement procedure that its equations appear in the profit optimization problems of market players.

3.1. Forward contracts agreement modeling

In forward market, every producer i and every consumer j are allowed to have a contract with each other. Different methods have already been introduced in the literature for modeling the forward market, [12 13]. Based on [12] each producer submits a fixed value to each consumer. Each consumer is modeled by a prices-taker load and accepts the price offer of the producers. In this paper, the proposed model in [12] is improved to provide a more realistic model for forward market. The supply function model is used to model the behavior of market players in the forward market. It is assumed that both producers and consumers are strategic in the forward market. Each producer submits different bids to different consumers. Each consumer considers different offer functions for each bid function that receives from the producers. The slope of the bid/offer functions of each producer/consumer is equal to the slope of his or her marginal cost/utility function. Producers/consumers game on the intercept of their bid/offer functions to find the optimal intercept for each consumer/producer. The agreed price and quantity of each contract are obtained by the intersection of bid and offer functions of contract parties. In more detail, each producer i submits a bid function to each consumer j as below:

$$F_{ij}^{fp} = \alpha_{ij}^f + b_i Q_{ij}^{fp} \tag{4}$$

where α_{ij}^f is the intercept of bid function of producer i and its decision variable in contract with consumer j, and F_{ij}^{fp} and Q_{ij}^{fp} are the proposed contract price and quantity of producer i to consumer j, respectively. Each consumer j submits an offer function to producer i as below:

$$F_{ji}^{fc} = \epsilon_{ji}^f - d_j Q_{ji}^{fc} \tag{5}$$

where ϵ_{ji}^f is the intercept of offer function of consumer j and its decision variable in contract with producer i, and F_{ji}^{fc} and Q_{ji}^{fc} are the proposed contract price and quantity of consumer j to producer i, respectively. The intersection of these two functions, i.e., taking into account that $F_{ij}^{fp} = F_{ji}^{fc}$ and $Q_{ij}^{fp} = Q_{ji}^{fc}$, yields the agreed quantity and the price of the contract between producer i and consumer j as below [17]:

$$Q_{ji}^{fc} = Q_{ij}^{fp} = \frac{\epsilon_{ji}^f - \alpha_{ij}^f}{b_i + d_j} \tag{6}$$

$$F_{ji}^{fc} = F_{ij}^{fp} = \frac{b_i\,\epsilon_{ji}^f + d_j \alpha_{ij}^f}{b_i + d_j} \tag{7}$$

3.2. Day-ahead electricity market modeling

In the contracting period, different wind power uncertainty scenarios are considered for the day-ahead electricity market in the delivery period. So, in the contracting period, results of the day-ahead market at each scenario s are required. Now, in order to model the day-ahead market at each scenario, we should take into account the impacts of the contracted powers in the contracting period on the bids of market players. From the viewpoint of the ISO, the producers submit affine bid functions in the form of $\alpha_{i,s}^d + b_i Q_{i,s}^{dp}$ to sell the rest of their free generation capacity in the day-ahead market. Consumers offer their marginal utility functions to the ISO. The total forward power of consumers should be subtracted from their total required power. So, the marginal utility function of consumer j for the day-ahead electricity market will be as below [17]:

$$MU_{j,s} = (c_j - d_j \sum_{i\in P} Q_{ji}^{fc}) - d_j Q_{j,s}^{dc} \tag{8}$$

So, social welfare maximization problem of the ISO in wind power uncertainty scenario s at day-ahead electricity market is formulated as below:

$$\max S_s = \sum_{j\in C} ((c_j - d_j \sum_{i\in P} Q_{ji}^{fc}) Q_{j,s}^{dc} - \frac{1}{2} d_j Q_{j,s}^{dc2}) - \sum_{i\in P} \left(\alpha_{i,s}^d Q_{i,s}^{dp} + \frac{1}{2} b_i Q_{i,s}^{dp2}\right) \tag{9}$$

$$s.\ t.\ \sum_{i\in P} Q_{i,s}^{dp} + Q_s^w - \sum_{j\in C} Q_{j,s}^{dc} = 0, \qquad (\lambda_s^d) \tag{10}$$

$$Q_{i,s}^{dp} + \sum_{j\in C} Q_{ij}^{fp} \le \bar{Q}_i^p \qquad (\bar{\mu}_{i,s}^{dp}) \tag{11}$$

$$-(Q_{i,s}^{dp} + \sum_{j\in C} Q_{ij}^{fp}) \le -\underline{Q}_i^p \qquad (\underline{\mu}_{i,s}^{dp}) \tag{12}$$

$$Q_{j,s}^{dc} + \sum_{i\in P} Q_{ji}^{fc} \le \bar{Q}_j^c \qquad (\bar{\mu}_{j,s}^{dc}) \tag{13}$$

$$-(Q_{j,s}^{dc} + \sum_{i\in P} Q_{ji}^{fc}) \le -\underline{Q}_j^c \qquad (\underline{\mu}_{j,s}^{dc}) \tag{14}$$

The first term of the objective function (9) represents the integration

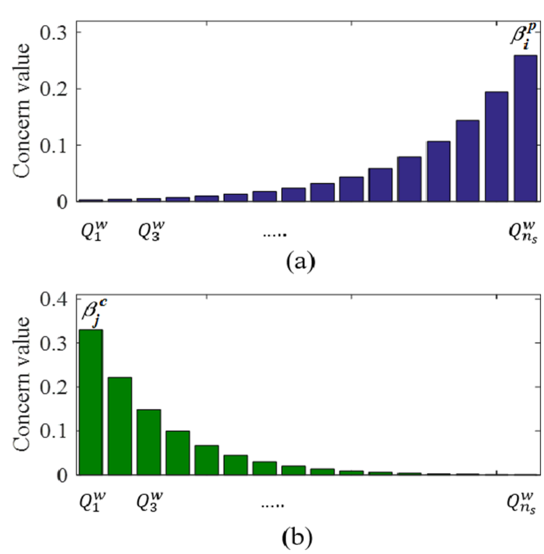

Fig. 3. Concern values of a) producer i and b) consumer j using Exponential distribution.

of utility functions of consumers that indicates the total utility of consumers from consuming electricity. The second term of (9) represents the integration of bid functions of the producers that implies the total money that the producers are willing to receive for selling energy. In fact, according to (9), by solving this optimization problem, ISO buys the electricity from the producers that bid the lower prices and sell the electricity to the consumers that offer higher prices for electricity. λ_s^d is the Lagrangian multiplier for constraint (10) and represents the MCP at scenario s in uniform pricing method [18]. Variables $\bar{\mu}_{i,s}^{dp}$, $\underline{\mu}_{i,s}^{dp}$, $\bar{\mu}_{j,s}^{dc}$, and $\underline{\mu}_{j,s}^{dc}$ are Lagrangian multipliers related to constraints (11)-(14), respectively [18]. The output powers of the producer's units are limited to their maximum and minimum values in (11) and (12). Constraints (13) and (14) consider the upper and lower bounds of consuming energy by consumers. The Decision variables of the ISO optimization problem (9)-(14) are the scheduled powers of consumers and producers and market-clearing i.e. $Q_{j,s}^{dc}\ \forall\, j \in C$, $Q_{i,s}^{dp}\ \forall\, i \in P$, and λ_s^d.

In the case that there are other uncertainties in the power generation like uncertainty in the output power of the photovoltaic panels, these uncertainties can be aggregated with the uncertainty of the wind farms and involved in Q_s^w. Since the output power of the wind farms is much more uncertain than other resources, the focus of this paper is on the wind power uncertainty.

4. SFE of the contracting period

4.1. Equilibrium model for UFUD model

As mentioned before, in the contracting period forward market and different scenarios for the day-ahead market in the delivery period are considered. In this section, first, the profit optimization problems of producers and consumers are presented. Then, the SFE calculation process is explained.

4.1.1. Producers' profit formulation in UFUD case

In the contracting period, each producer tries to maximize his/her expected profit in the aggregation of the forward contracts and different outcomes of the day-ahead market. Moreover, risk management preferences of market players are also considered in the model using upgraded concern scenarios. Therefore, the optimization problem of the producer i is formulated as below:

$$MaxE(P_i) = \sum_{s\in S}\rho_{i,s}^{p}\left[\lambda_s^d Q_{i,s}^{dp} + \sum_{j\in C}F_{ij}^{fp}Q_{ij}^{fp} - a_i\left(Q_{i,s}^{dp} + \sum_{j\in C}Q_{ij}^{fp}\right) - \frac{1}{2}b_i\left(Q_{i,s}^{dp} + \sum_{j\in C}Q_{ij}^{fp}\right)^2\right] \tag{15}$$

$$s.\ t.\ : Q_{i,s}^{dp} \geq 0(\mu_{i,s}^{dp+}) \qquad \forall\, s \in S \tag{16}$$

$$Q_{ij}^{fp} \geq 0(\mu_{ij}^{fp}) \qquad \forall\, j \in C \tag{17}$$

$\rho_{i,s}^{p}$ represents the concerns of producer i about wind power generation in different scenarios of the delivery period. The first and second terms of the objective function (15) are the revenues from the day-ahead and forward markets, respectively. The last term represents the total cost of the producer i. Decision-making variables of producer i are $\alpha_{ij}^c\ \forall\, j \in C$ and $\alpha_{i,s}^d\ \forall\, s \in S$. Constraints (16)-(17) guaranty the positivity of the day-ahead market power and forward contract power of producer i.

4.1.2. Consumer's profit formulation in UFUD case

The profit of each consumer is calculated by subtracting the utility of electricity for that consumer from the payment in the forward and

Table 1
Producers cost function parameters.

	Producer number P1	P2	P3	P4	P5
$a_i(\$/MWh)$	17	10	7.6	26	24
$b_i(\$/MW^2h)$	0.007	0.010	0.013	0.005	0.017
$\bar{Q}_i^p(GW)$	2.5	3	2.2	2	1.5
$\underline{Q}_i^p(GW)$	0.5	0.7	0.2	0.8	0.5

Table 2
Consumers utility function parameters.

	Consumer number C1	C2	C3	C4	C5	C6
$c_j(\$/MWh)$	64	62	66	63	70	69
$d_j(\$/MW^2h)$	0.013	0.007	0.015	0.01	0.025	0.02
$\bar{Q}_i^c(GW)$	2.1	3.2	2	2.7	1.35	1.45
$\underline{Q}_i^c(GW)$	1.65	3	1.5	2	1.2	1.3

Table 3
Coefficients of Exponential PDFs for generating concern scenarios of market players.

	Producer number P1	P2	P3	P4	P5	Consumer number C1	C2	C3	C4	C5	C6
$\beta_i^p \& \beta_i^c$	0.35	0.3	0.3	0.4	0.5	0.3	0.2	0.4	0.2	0.5	0.4

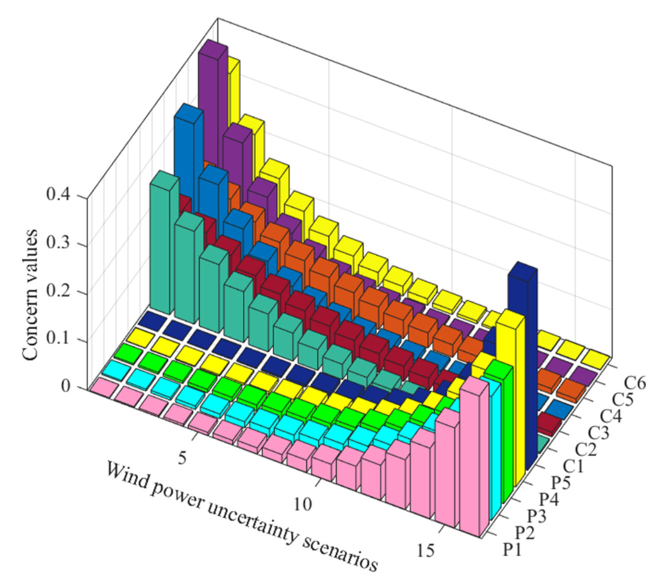

Fig. 4. Concern values of different market players in different scenarios.

Table 4
Forward contract quantities ($Q_{ij}^{cp}(MW)$) between different producers and consumers in uniform pricing model.

	C1	C2	C3	C4	C5	C6	Total
P1	152	225	141	175	112	122	**927**
P2	190	261	176	214	140	153	**1136**
P3	144	193	135	160	113	121	**856**
P4	213	321	192	248	144	161	**1281**
P5	137	177	131	150	111	118	**825**
Total	**836**	**1177**	**776**	**948**	**620**	**677**	

day-ahead markets. The optimization problem of consumer j is formulated as below:

$$\max E(U_j) = \sum_{s\in S} \rho^c_{j,s}\left[c_j\left(Q^{dc}_{j,s} + \sum_{i\in P} Q^{fc}_{ji}\right) - \frac{1}{2}d_j\left(Q^{dc}_{j,s} + \sum_{i\in P} Q^{fc}_{ji}\right)^2 - \lambda^d_s Q^{dc}_{j,s} - \sum_{i\in P} F^{fc}_{ji} Q^{fc}_{ji}\right] \tag{18}$$

$$s.\ t\ Q^{dc}_{j,s} \geq 0(\mu^{dc+}_{j,s}) \qquad \forall\ s \in S \tag{19}$$

$$Q^{fc}_{ji} \geq 0(\mu^{fc}_{ji}) \qquad \forall\ i \in P \tag{20}$$

$\rho^c_{j,s}$ represents the concerns of consumer j about wind power generation in different scenarios of the delivery period. The first two terms of (18) correspond to the total utility of consuming power of the consumer j, and the last two terms are the costs of buying power from day-ahead and forward markets, respectively. Constraints (19) and (20) guaranty the positivity of the day-ahead and contract powers.

4.1.3. Obtaining the SFE of the UFUD model

Nash equilibrium of a system is referred to as a situation in which none of the market players can increase their profit by changing their behavior in the system unilaterally. The process of obtaining the SFE for each case is similar to the proposed method in [17] and [18]. In order to find the SFE of the model, the optimization problems market players should be solved together considering day-ahead electricity markets and forward contract outcomes. This turns the optimization problems of market players into coupled bi-level optimization problems. Profit optimization problems of producers/consumers, i.e. (15)-(17) / (18)-(20), are the outer-level problems. The forward market problem, i.e. (6)-(7), and ISO optimization problem, i.e. (9)-(14), are two inner-level problems of each outer-level problem. The outer-level problems are coupled and form an equilibrium problem with equilibrium constraints (EPEC). The solution of the EPEC is SFE. A straightforward method to solve this bi-level optimization problem is to substitute the inner-level optimization problems with their KKT optimally conditions and add them to the optimization problems of all market players as constraints. This turns the bi-level optimization problem into a single-level optimization problem. Now, in order to find the SFE, KKT optimally conditions of optimization problems of all producers and consumers should be solved together. Below steps explains this process in more details:

a) Applying a process similar to the proposed method in [19] and [20], using the KKT optimally conditions of the ISO optimization problem (9)-(14) the scheduled power of producers ($Q^{dp}_{i,s}$) and consumers ($Q^{dc}_{j,s}$) and the MCP (λ^d_s) are computed as functions of market players decision variables, i.e., $\alpha^d_{i,s}$, α^f_{ij}, ϵ^f_{ji} as below [1920]:

$$Q^{dp}_{i,s} = \frac{1}{Bb^e_i}\left[\sum_{j\in C}\frac{c_j - \mu^{dc}_{j,s}}{d_j} - \sum_{j\in C}\sum_{i\in P} Q^{fc}_{ji} - Q^w_s\right] + \sum_{u\in P} m^i_u(\alpha^d_{u,s} + \mu^{dp}_{u,s})$$
$$\forall\ i \in P,\ s \in S \tag{21}$$

$$Q^{dc}_j = \frac{-1}{d^e_j}\sum_{l\in C} Z^j_l(c_j - \mu^{dc}_{j,s}) + \sum_{l\in C}\sum_{i\in P}\frac{d_l}{d_j}Z^j_l Q^{fc}_{li} + \frac{1}{Bd_j}Q^w_s - \sum_{u\in P}\frac{\alpha^d_{u,s} + \mu^{dp}_{u,s}}{Bd_j b_u} \qquad \forall\ j \in C,\ s \in S \tag{22}$$

Table 6
Forward contract prices ($F^c_{ij}(\$/MWh)$) between different producers and consumers in uniform pricing model.

	C1	C2	C3	C4	C5	C6	Eq. price
P1	39.5	39.5	39.6	39.5	39.9	39.8	**39.6**
P2	40.1	39.9	40.3	39.9	40.7	40.5	**40.2**
P3	39.5	39.3	39.6	39.4	40.1	39.8	**39.6**
P4	40.2	40.1	40.3	40.1	40.7	40.5	**40.3**
P5	39.6	39.4	39.8	39.5	40.2	40.1	**39.8**
Eq. price	**39.8**	**39.7**	**40**	**39.9**	**40.4**	**40.2**	

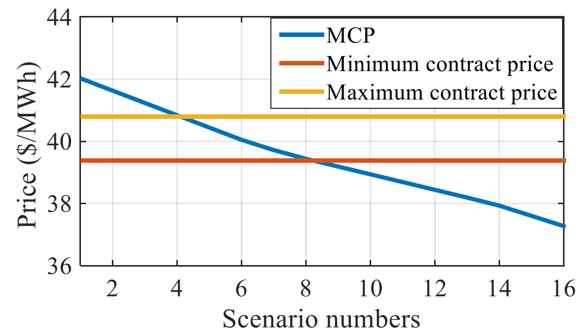

Fig. 5. Comparing day-ahead market price and maximum and minimum forward contract prices in the uniform pricing model.

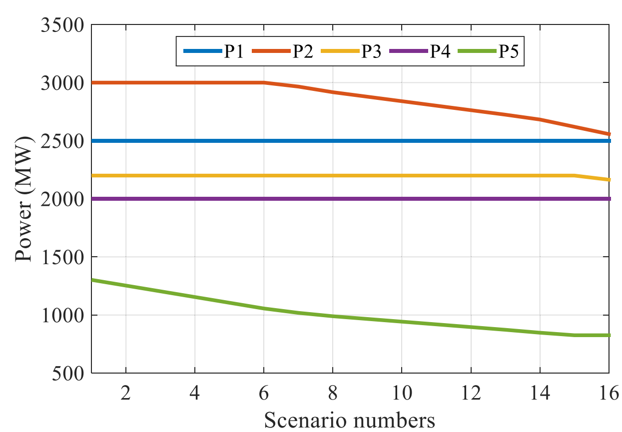

Fig. 6. Total scheduled power of producers in the both day-ahead and forward markets in the uniform pricing model.

$$\lambda^d_s = \frac{1}{B}\left(\sum_{j\in C}\frac{c_j - \mu^{dc}_{j,s}}{d_j} - \sum_{j\in C}\sum_{i\in P} Q^{fc}_{ji} - Q^w_s + \sum_{u\in P}\frac{\alpha^d_{u,s} + \mu^{dp}_{u,s}}{b_u}\right)$$
$$\forall\ s \in S \tag{23}$$

where:

$$\mu^{dp}_{i,s} = \bar{\mu}^{dp}_{i,s} - \underline{\mu}^{dp}_{i,s} \quad \forall\ i \in P,\ s \in S \tag{24}$$

$$\mu^{dc}_{j,s} = \bar{\mu}^{dc}_{j,s} - \underline{\mu}^{dc}_{j,s} \qquad \forall\ j \in C,\ s \in S \tag{25}$$

Table 5
Comparing the total volume of contracts and expected volumes of scheduled powers in day-ahead market in UFUD model.

	Producers					Consumers					
	P1	P2	P3	P4	P5	C1	C2	C3	C4	C5	C6
Forward contracts	927	1136	856	1281	825	836	1177	776	948	620	677
Day-ahead market	1572	1723	1331.9	719.2	185.4	1122	1894.3	991.7	1404	616.4	753.4
Ratio	0.59	0.66	0.65	1.78	4.45	0.75	0.62	0.78	0.67	1.01	0.89

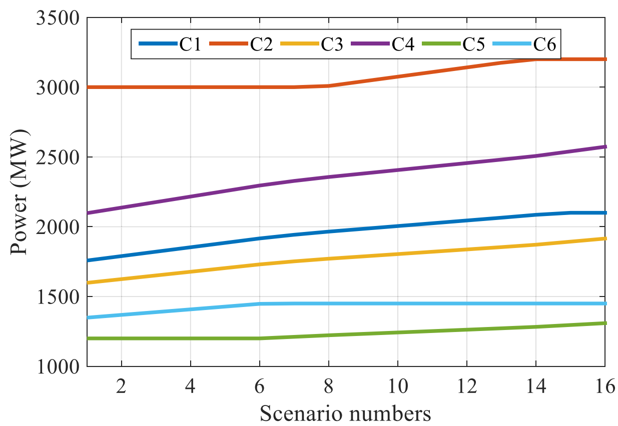

Fig. 7. Total scheduled power of consumers in the both day-ahead and forward markets in the uniform pricing model.

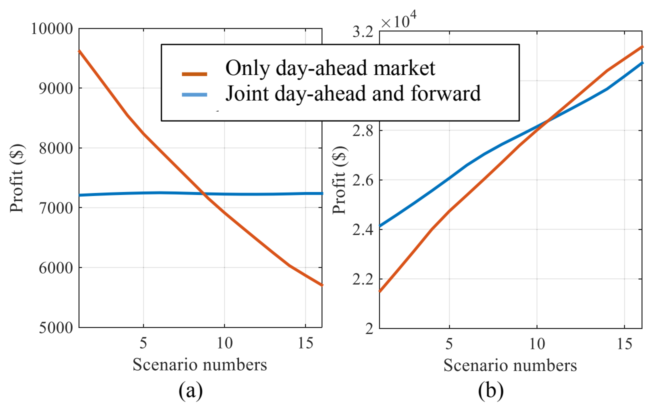

Fig. 8. Comparing the profit of a) P5 and b) C4 in considering and without considering forward market in uniform pricing model.

$$B = \sum_{i \in P} \frac{1}{b_i} + \sum_{j \in C} \frac{1}{d_j} \tag{26}$$

$$m_u^i = \begin{cases} \frac{1}{Bb_u b_i} & i \neq u \\ \frac{1}{Bb_u}\left(\frac{1}{b_u} - B\right) & i = u \end{cases} \quad \forall\ i, u \in P \tag{27}$$

$$Z_l^j = \begin{cases} \frac{1}{Bd_j} & j \neq l \\ \frac{1}{Bd_j} - 1 & j = l \end{cases} \quad \forall\ j, l \in C \tag{28}$$

b) Equations (6), (7), (11)-(14), and (21)-(23) are substituted with the inner optimization problems in the optimization problems of producers and consumers i.e. (15)-(17) and (18)-(20). These optimization problems are now called the revised optimization problems of producers and consumers.

c) Revised optimization problems are in the form of quadratic programming problems and hence, are convex. Write the KKT optimally conditions of all revised optimization problems of producers and consumers.

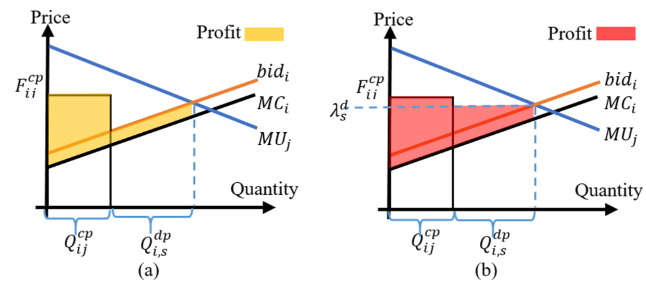

Fig. 9. Graphical representation of profit of producers in a) pay-ab-bid model and b) uniform model.

d) Now, in order to find the SFE of the models, KKT optimally conditions of revised optimization problems of all producers and consumers should be solved together.

Following the abovementioned steps, optimal decision-making variables of producers in the forward market i.e., α_{ij}^{f*}, and different scenarios for the day-ahead electricity market, i.e., $\alpha_{i,s}^{d*}$, and optimal decision-making variables of consumers in the forward market, i.e., ϵ_{ji}^{f*} are obtained. However, since the market players are in the contracting period, only the optimal decision-making variables for the forward market can be applied to determine the contract prices and quantities. The obtained decision-making variables for different scenarios of the day-ahead market in contracting period can be used for estimating the day-ahead market in the future.

Comparing (21)-(23) with the proposed formulation in [16] shows that while the process of finding the SFE in both models are similar, there are differences between these two models. Equations (21)-(23) involve a term related to wind power generation. More importantly, in this paper, the upper and lower limits of loads are modeled in the ISO optimization problem as well as the power generation capacity of the producers. This makes the equations (21)-(23) dependent on the Lagrangian dual variables of producers' power generation constraints and consumers' energy consumption constraints.

Based on the above-mentioned explanation, Nash equilibrium of the joint day-ahead and forward markets is a generalized Nash equilibrium that is referred to as Nash equilibrium for the sake of simplicity [21].

4.2. Equilibrium model for UFPD model

The difference between the uniform and bay-as bid models is about the revenue of the producers and the cost of the consumers from the day-ahead market.

4.2.1. Producers' profit formulation in SFE-UFPD case

In UFPD case, according to proposed formulation in [22], for each producer i, the phrase $\lambda_s^d Q_{i,s}^{dp}$ in (15) is replaced with $\alpha_{i,s}^d Q_{i,s}^{dp} + \frac{1}{2} b_i Q_{i,s}^{dp2}$. Rewriting and rearranging the (15) the optimization problem is formulated as below:

Table 7
Comparing the total volume of contracts and expected volumes of scheduled powers in the day-ahead market in UFPD model.

	Producer number					Consumer number					
	P1	P2	P3	P4	P5	C1	C2	C3	C4	C5	C6
Forward contracts	1934	2016	1733	1582	817	1345	1632	1298	1436	1161	1211
Day-ahead market	559	565	407.9	416.3	118.2	515	1391	385.4	789.4	53.1	183.7
Ratio	3.45	3.56	4.25	3.80	6.91	2.61	1.17	3.37	1.81	21	6.59

Table 8
Equivalent contract prices in pay-as-bid model.

	Producer number					Consumer number					
	P1	P2	P3	P4	P5	C1	C2	C3	C4	C5	C6
Equivalent contract prices ($/MWh)	38.9	38.5	37.9	39.8	39.5	38.6	38.1	38.9	38.3	39.9	39.4

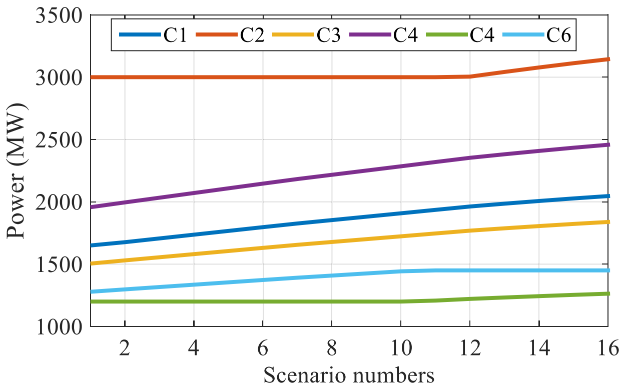

Fig. 10. Total scheduled power of producers in day-ahead and forward markets in the pay-as-bid pricing model.

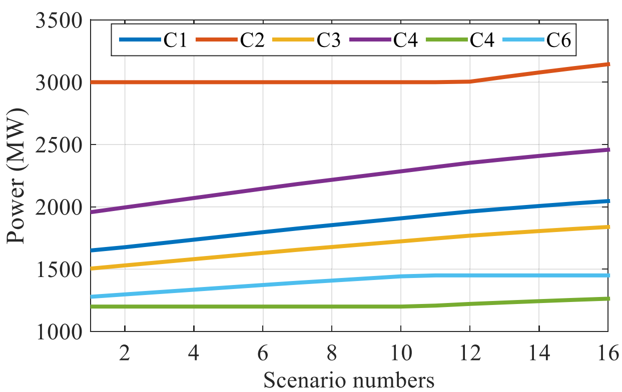

Fig. 11. Total scheduled power of consumers in day-ahead and forward markets in the UFPD model.

$$MaxE(\pi_i) = \sum_{s\in S}\rho_{i,s}^{p}\left[\sum_{j\in C}F_{ij}^{fc}Q_{ij}^{fc} + \left(\alpha_{i,s}^{d} - a_i - b_i\sum_{j\in C}Q_{ij}^{fp}\right)Q_{i,s}^{dp} - a_i\sum_{j\in C}Q_{ij}^{fp} - \frac{1}{2}b_i\left(\sum_{j\in C}Q_{ij}^{fp}\right)^2\right] \quad (29)$$

$$s.\ t.\ :Q_{i,s}^{dp} \geq 0(\mu_{i,s}^{dp+}) \qquad \forall\ s \in S \quad (30)$$

$$Q_{ij}^{fp} \geq 0(\mu_{ij}^{fp})\ \forall\ j \in C \quad (31)$$

4.2.2. Consumers' profit formulation in SFE-UFPD case

Consumers are price takers in the Day-ahead market. Hence, their offers in the day-ahead market are equal to their utilities. On the other hand, in pay-as-bid pricing mechanism, electricity price is equal to the submitted bid to the ISO. So, the profit of the consumers from the day-ahead market will be equal to zero if the pay-as-bid pricing method is used. In this condition, the optimization problem of consumer j is formulated as below:

$$\max E(U_j) = \sum_{s\in S}\rho_{j,s}^{c}\left[c_j\left(\sum_{i\in P}Q_{ji}^{fc}\right) - \frac{1}{2}d_j\left(\sum_{i\in P}Q_{ji}^{fc}\right)^2 - \sum_{i\in P}F_{ji}^{fc}Q_{ji}^{fc}\right] \quad (32)$$

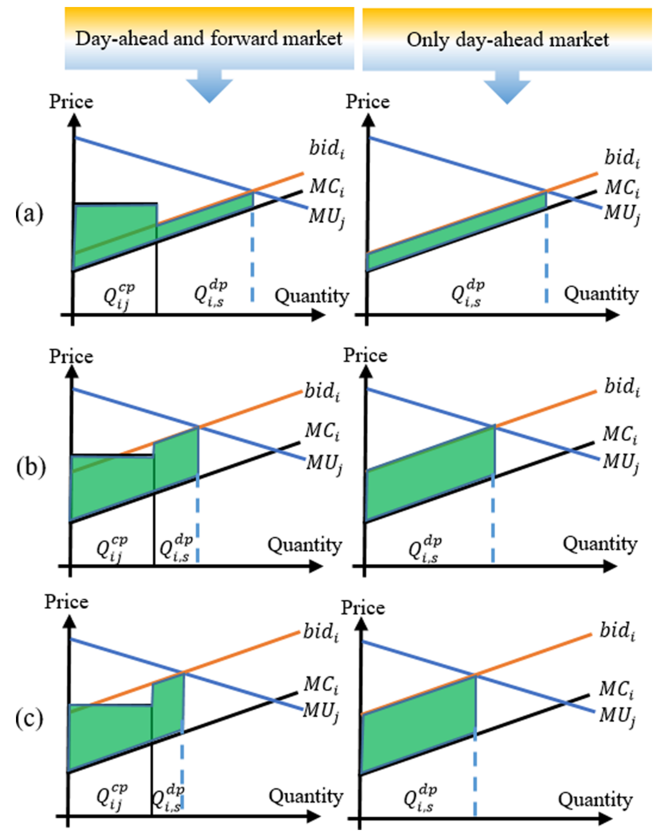

Fig. 12. Comparing the profit of a) P5, b) P1 and c) P3 with and without considering forward market in pay-as-bid pricing model.

$$s.\ tQ_{j,s}^{dc} \geq 0(\mu_{j,s}^{dc+}) \qquad \forall\ s \in S \quad (33)$$

$$Q_{ji}^{fc} \geq 0(\mu_{ji}^{fc}) \qquad \forall\ i \in P \quad (34)$$

4.2.3. Obtaining the SFE of the SFE-UFPD model

A process similar to the section A.3 is repeated to find the SFE in this model. The only difference is that in the pay-as-bid model, equation (23) is not required in the SFE calculation process.

5. SFE of the delivery period

As mentioned before, there are two games in the system. A game in the contracting period between producers and consumers, and a game between producers at the day-ahead market in the delivery period. The first game was modeled in the previous section. The second game is formulated as follows. It should be noted that in the delivery period, 1) one of the wind power uncertainty scenarios happens, 2) forward contract market is closed but impacts of its results on the day-ahead market should be considered, and 3) only producers participate in the day-ahead market strategically. Considering below modifications in the presented approaches in section IV, the SFE models for both UD and PD models can be obtained from UFUF and UFPD models, respectively:

1) Problems are solved for one scenario.

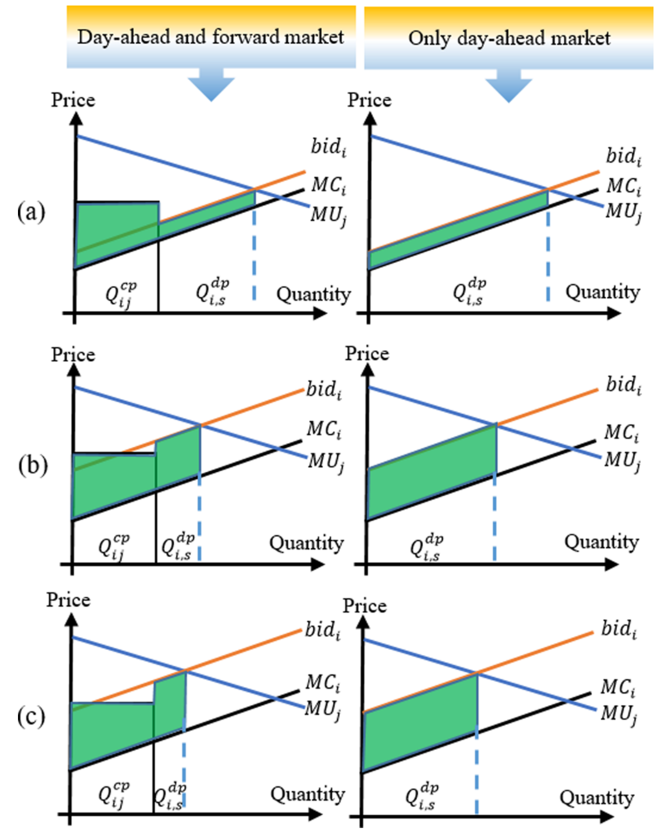

Fig. 13. Comparing the profit of producers in joint day-ahead and forward market and only day-ahead market case in pay-as-bid model in different possible situations.

Table 9
Comparing the simulation results for producers with constant marginal cost functions in uniform and pay-as-bid models.

	Uniform	Pay-as-bid
Total contracted power (MW)	2112	1923
Scheduled power in day-ahead market (MW)	388	577
Total scheduled power (MW)	2500	2500
Expected profit ($)	46,642	45,219
Ratio	5.44	3.33

2) Q_s^w in the formulations is considered as the final forecasted wind power.
3) The values of Q_{ij}^{fp}, Q_{ji}^{fc}, F_{ij}^{fp} and F_{ji}^{fc} are considered as constants in the formulations, equal to the obtained values in the UFUD and UFPD models.
4) Optimization problems of consumers i.e., (12)-(14) for UFUD case and (28)-(30) for UFPD case are omitted from the Nash equilibrium calculation procedure presented in section IV.A.3.
5) Now, following the Nash equilibrium calculation steps presented in section IV.A.3 the SFE of the UD and PD models can be found

In this condition, the only decision-making variables of market players are the bids of producers in the day-ahead electricity market i.e., $\alpha_{i,s}^{dp}$. Using $\alpha_{i,s}^{dp}$, the scheduled power of market players and market price can be found using (17)-(19)

6. Numerical results

The understudy test system includes 5 producers and 6 consumers. Producers' data are presented in Table 1. As mentioned before, each producer can own a group of generation units. In order to avoid complexity in the model, all generating units of producers are aggregated in a single unit and a single affine marginal cost function is assigned to each producer as shown in Table 1. Consumers' data are presented in Table 2. Consumers' data are chosen such that day-ahead electricity market prices get close to the real-world electricity prices. Indices "P" and "C" refer to the producers and consumers, respectively. The installed capacity of wind power is 2.5 GW. Sixteen discrete scenarios are generated for wind power generation uncertainty between 0 and 2.5 GW uniformly i.e., $Q_s^w = \{0GW, 0.166GW, 0.333GW, \cdots, 2.5GW\}$. Parameters β_i^P and β_i^c of risk management preferences of market players are presented in Table 3. These values are determined such that a wide range of concerns for all market players is covered. Fig. 4 represents the concern values of producers and consumers in different scenarios. Since the output power of the WFs increases by increasing the scenario number index, according to discussions in section II.C, the concern values of producers/consumers increase by increasing/decreasing the assigned number of scenarios. Differences in the concern values of market players are because of differences in the concerns of market players about the future which is modeled by assigning different values for β_i^P and β_i^c. Based on information in Table 3 and Fig. 3, producer 5 and consumer 5 have the most concerns about the delivery period.

6.1. Simulation results of the uniform pricing models

In this subsection, the simulation results of the market players' gaming in the contracting period and delivery period for the uniform pricing model are presented. To this end, first, SFE for the UFUD model is obtained and quantities and prices of different contracts and estimations for day-ahead market prices and quantities in different scenarios are obtained. However, only the information related to the forward contracts is considered. Then the UD model is executed for each scenario of delivery period separately considering the contracted prices and volume of forward contracts and the results are presented. Forward contract prices and quantities for all market players obtained from the UFUD model are presented in Tables 4 and 6, respectively. For each market player, the sum of the quantities of forward contracts i.e., $Q_i^p = \sum_{j\in C} Q_{ij}^{cp}$ for producer i and $Q_j^c = \sum_{i\in P} Q_{ji}^{cc}$ for consumer j is considered as his/her total contract power quantity. As Table 4 shows, P4 and C2 contract more quantity of power than other producers and consumers, respectively. Moreover, P5 and C6 have the lowest quantities of contracted powers. In order to compare the impacts of concern values to the results, the results of the both contracting and delivery periods should be considered simultaneously. Table 5 presents the total contract power quantities, average scheduled power in the day-ahead market and the ratio of contract power quantities to the average scheduled power in the day-ahead market. As Table 5 shows, P4 and P5 that have the highest concerns compared to the other producers have greater ratio values, and C5 and C6 that have more concerns than other consumers, have greater ratio values than other consumers. This shows that as the concerns of market players in the contracting period about the delivery period increase the share of the forward contracts from their traded power in the system increases which is reasonable and indicates the efficiency of the proposed risk management method.

The weighted average of contract prices of each market player is considered as the equivalent contract price for that market player. According to Table 6, P1, P3 and C2 have the lowest contract prices and the lowest contract price belongs to the contract between P3 and C2. P4 and C5 have the highest contract prices and their forward contract has the highest contract price among all contracts. Fig. 5 compares the MCP in different scenarios with the contract prices. MCP decreases by increasing the scenario number index i.e., generated power by WFs. In fact, since the WFs have priority for generating power, increasing the generated power by the WFs, reduces the remained demand for other producers, increases the competition and consequently, reduces the MCP. As shown in Fig. 5, contract prices are obtained such that their values are close to the expected MCP in the delivery period. Contract prices are greater than the MCP in the last 8 scenarios i.e., the scenarios that the producers are more worried about them, and lower than the MCP in the most of first 8 scenarios, i.e., the scenarios that the consumers are more worried about them.

Fig. 6 and Fig. 7 present the variation of total scheduled power (sum of contract powers and day-ahead scheduled powers) of producers and consumers in different scenarios, respectively. According to Fig. 6, P1 and P4 sell all their capacity in the aggregation of contracts and the day-ahead market in different scenarios. The generated power of other producers reduces by increasing the generated power of the WFs. In fact, by increasing the output power of the WFs, the residual electricity demand and consequently share of each market player from total demand decreases. Fig. 7 shows that both lower and upper power-consuming limits of C2 can be activated based on which scenario happens. Lower power-consuming bound of C5 and upper power-consuming limits of C1 and C6 are also activated in different scenarios. Power consumption of consumers increases as the generated power by the WFs increases. This happens because according to Fig. 5, the MCP reduces by increasing the generated power by WFs which encourages the consumers to consume more electricity.

As mentioned before, financial derivatives are used to reduce the profit dependence on uncertainty and the risk of losing money for both producers and consumers. In order to highlight this feature, simulations are performed and compared for two cases, 1) proposed method in this paper i.e., considering both day-ahead and forward markets and 2) considering only the day-ahead market in the system. In order to model the case 2, it is enough to set the contract price and quantities equal to zero in section V. Simulation results are compared for P5 and C4 in Fig. 8. P5 has the highest concerns and C4 has the lowest concerns about the delivery period. According to Fig. 8, high concerns of P5 has led to selling the most of generation capacity in the forward market. This causes fixed revenue for the P5 and hence, reducing the variation in the profit as much as possible. In this case, P5′s profit gets almost independent from the uncertainty of WFs' output power. Low concerns of the C5 results in more variability in the profit compared to the profit of the P5. However, the variation of profit for C5 in the case of participation in the forward market is lower than the case that the C5 participates only in the day-ahead market due to the fixed utility of the C5 from the forward contracts.

6.2. Simulation results of the pay-as-bid pricing models

In this subsection, the simulation results of the pay-as-bid pricing model are presented. To this end, first, SFE for the UFPD model is obtained and quantities and prices of different contracts and estimations for the day-ahead market prices and quantities in different scenarios are obtained. Then SFE for the PD model is obtained considering the contracted prices and volume of the forward market. The basic analysis of this subsection is similar to the results of the subsection VI. A. In order to avoid repetitive explanations, the focus of this subsection is on comparing the results of the pay-as-bid model with the uniform model of the day-ahead market beside the forward market.

Table 7 compares the share of the forward contracts obtained from UFPD model and the day-ahead market obtained from PD model for different market players in the pay-as-bid model. Comparing the results of Tables 7 and 5 indicates that the share of the forward contracts from the total traded power in the system increases considerably in the pay-as-bid model.

In order to explain this difference, a simple graphical presentation for the profit of an arbitrary producer *i* is presented in Fig. 9. As shown in Fig. 9, the profit of producers from the day-ahead market in the pay-as-bid model can be lower than their profit from the day-ahead market in the uniform model. Hence, forward contracts can be chosen as a useful tool for producers to increase their profit in the system. This leads to an increase in the power quantities of the forward contracts in the pay-as-bid model compared to the uniform model. Similar explanations can be presented for consumers.

Equivalent forward contract prices for different market players in the pay-as-bid model are presented in Table 8. Comparing the results of Table 8 and Table 6 shows that contract prices in the pay-as-bid model are about 3% less than contract prices in the uniform model. In fact, increasing the participation of market players in the forward market for increasing their profit, increases the competition in this market and leads to reduction in the contract prices.

The total scheduled powers of producers and consumers in the pay-as-bid model are presented in Fig. 10 and Fig. 11, respectively.

Comparing the results of Fig. 7 and Fig. 11 with the results of Fig. 6 and Fig. 7 indicates that the total scheduled power in the pay-as-bid model is lower than the total scheduled power in the uniform model. In fact, increasing the competition in the forward market at the pay-as-bid model reduces the competition in the day-ahead market such that the level of competition in the whole system decreases and this leads to lower aggregated scheduled power in the pay-as-bid model.

In the pay-as-bid model, since the consumers' electricity price is equal to their marginal utility function, their profit from the day-ahead market is equal to zero. The forward contract prices and quantities are the same in different scenarios. So, the profit of consumers in the pay-as-bid model is constant in all scenarios. On the other hand, different situations can happen for producers in the pay-as-bid model. Fig. 12 compares the profits of P5, P1, and P3 in the case of participation in both forward and day-ahead markets and participation in only the day-ahead market at different scenarios. In all cases, the variation in the profit of market players reduces after participation in the forward market parallel with the day-ahead market. However, in Fig. 12(a), the profit of P5 in the joint forward and day-ahead markets is less than his/her profit in only the day-ahead market case at almost all scenarios, in Fig. 12(b), the profit of P1 in the joint forward and day-ahead markets is less than his/her profit in the only day-ahead market case at some of t he scenarios, and in Fig. 12(c), the profit of P3 in the joint forward and day-ahead markets is more than his/her profit in the only day-ahead market case at all scenarios. In order to explain how the profit in joint day-ahead and forward markets get less or more than the profit in the only day-ahead market case, a simple graphical presentation of the profit of an arbitrary producer *i* in pay-as-bid modeling case at the different situation is compared in Fig. 13. The highlighted area represents profit. Based on Fig. 13, according to the position of the bid function (bid_i) and contract prices and quantities, the profit of producer *i* changes. In Fig. 13 (a) when the bid function is close to the marginal cost function (MC_i) the profit in the joint day-ahead and forward markets gets more than the profit in the only day-ahead market case. As bid function gets far from the marginal cost function the profit in the joint day-ahead and forward markets decreases. In Fig. 13(b) the profits in two cases get almost equal, and in the Fig. 13(c) the profit in the joint day-ahead and forward markets gets less than the profit in the only day-ahead market case.

6.3. Studying the behavior of producers with fixed marginal cost functions

Some of the producers in the power system like nuclear power plants and hydropower plants have almost constant marginal cost functions. The behavior of these types of market players can be different from other market players. In order to study the behavior of these producers, producer P1 in Table 1 is replaced by a producer with the marginal cost function $MC_{1,s} = 20 + 0.00001Q_{i,s}^{dp}$. Simulation results for both uniform and pay-as bid models are presented in Table 9. The first point about the results in Table 9 is that the volume of the total forward contracts of these types of producers is high. Moreover, unlike the other market players, for these type of producers, the contract power quantities and scheduled power of the day-ahead market in uniform and pay as bid pricing methods are not significantly different. In fact, since the marginal cost of these producers is almost constant, their revenue from the day-ahead market in both uniform pricing and pay-as-bid pricing gets close to each other and this causes that their behavior in the contracting period also gets almost the same. More importantly, unlike the other producers, the total forward contract and profit for these types of producers in uniform pricing method obtain higher than the total contract power and profit in the pay-as-bid model.

7. Conclusions

In this paper, the behavior of the producers and consumers in forward and day-ahead electricity markets under the large-scale penetration of wind power was studied. The supply function model was used to model the market players' behavior in both forward and day-ahead markets. In order to study the impacts of pricing mechanisms on the results, the problem was modeled with both uniform and pay-as bid pricing models. The study was performed in the Nash equilibrium condition of the system. Two separate supply function equilibrium models for the contracting period and delivery period were proposed. However, the interactions between the market players' actions in the contracting period at the forward market and delivery period in the day-ahead market were considered in the models.

The proposed model considered the strategic behavior of consumers in the contracting negotiations, upper and lower power consumption limits for consumers and uncertainty related to wind power generation. Moreover, an upgraded risk management method was introduced and its efficiency discussed.

Simulation results showed that the prices of the forward contracts try to follow the expected value of prices of the day-ahead market but according to the amount of the wind power generation in the delivery period, contract prices may get lower or higher than the day-ahead market prices. When a market player is more concern about the delivery period, the share of his/her forward contracts of his/her total scheduled power increases. The quantity of the forward contracts in the pay-as bid model is more than their quantities in the uniform pricing model but total scheduled power in the pay-as-bid model is lower than the total scheduled power in the uniform model. Since in the pay-as-bid model, market players can increase their profit by the forward contracts more than in the uniform model, pay-as-bid pricing in comparison to uniform pricing increases competition/reduces prices at the forward market and reduces competition/increases prices at the day-ahead market. It should be noted that some of the obtained results in the paper might be case-dependent and different results might be obtained for other test systems. However, the proposed method is capable to be applied to different test systems. Simulation results also demonstrated the efficiency of the proposed risk management method in reducing the market players' profit dependency on uncertainties. The future directions of this work can include modeling the strategic behavior of wind power plants in the system, modeling the transmission congestion in the system, including the balancing market parallel with the day-ahead market, and considering the multistage involvement of market players in forward contracts during the contracting period.

CRediT authorship contribution statement

Mohsen Banaei: Conceptualization, Methodology, Software, Validation, Writing - original draft. **Hani Raouf-Sheybani:** Conceptualization, Methodology, Writing - review & editing. **Majid Oloomi-Buygi:** Conceptualization, Methodology, Resources, Writing - review & editing, Supervision. **Jalil Boudjadar:** Resources, Writing - review & editing, Supervision.

Declaration of Competing Interest

The authors declared that there is no conflict of interest.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijepes.2020.106450.

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